LESSONS LEARNED FROM USING SPACE DATA SYSTEMS STANDARDS IN FLIGHT MISSIONS

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ABSTRACT

Recommendations by the Consultative Committee for Space Data System (CCSDS) have been used in the development and operation of spacecraft at the Goddard Space Flight Center (GSFC) since 1991. Applying the Recommendations has reduced the cost and risk of spacecraft development and flight operations and provided proven solutions to user missions. Spacecraft projects will benefit even further from a future standard for file transfer and from application layer standards for common spacecraft operations functions.

KEYWORDS

CCSDS, standards, spacecraft operations, protocols

INTRODUCTION

Space data systems standards have an impact on the development and test of a spacecraft prior to launch and the on-orbit operations. The systems used for spacecraft testing and for mission operations generate commands and monitor telemetry data to determine the configuration and status of the spacecraft components. Formerly, spacecraft would use similar, but not identical protocols and formats for telemetry and command data. In the 1980s, the CCSDS developed a suite of Recommendations for space data communications and related aspects of the space/ground link. The first GSFC spacecraft to use CCSDS was the Solar Anomalous and Magnetosphere Particle Explorer (SAMPEX), launched in 1991. CCSDS Recommendations have been used for almost all Goddard Space Flight Center flight missions since then.

CCSDS

The CCSDS is a multi—space agency group, with members from North America, Europe, Japan, and elsewhere around the world. This committee was established in the early 1980s to assist in standardizing the space/ground links of the various agencies to increase the interoperability of their spacecraft and communications systems. The procedures of the CCSDS are described in reference [1]. CCSDS has established Recommendations for telemetry, telemetry coding, commanding, time codes, data formatting, and radio frequency and modulation. The telemetry and telecommand Recommendations are the ones that most directly impact the development and operation of flight systems.

The telecommand Recommendations define the formats, coding, and protocol for commanding a spacecraft. The protocol and coding assures a high probability that only correct, in-sequence commands are accepted by the spacecraft. The protocol provides an efficient mechanism for uplink to on-orbit spacecraft, where the communications latency is within a few seconds. The command protocol depends on a Command Link Control Word in the telemetry data to handle the acknowledgments. The command protocol also has features that allow the protocol to be bypassed. These features are typically used in non-nominal situations. The telecommand Recommendations are described in references [2], [3], [4], and [5].

There are two telemetry Recommendations. The first, Packet Telemetry [6], was developed in the mid-1980s and features up to 8 virtual channels. The second, Advanced Orbiting Systems (AOS) [7], was developed in 1989 for potential application to missions such as Space Station. AOS telemetry accommodates a more diverse set of data types, including voice and video. A subset of the AOS Recommendation, the Path Service, is similar to Packet Telemetry except that it supports 64 virtual channels.

CCSDS telemetry has two primary data constructs: the telemetry packet and the transfer frame, for Packet Telemetry, or Virtual Channel Data Units (VCDU), for AOS. The telemetry packet is a logically connected set of parameters. Telemetry packets are carried by a stream of fixed-length transfer frames/VCDUs, which provide a means of frame synchronization and error correction encoding. Each transfer frame/VCDU has a virtual channel identifier associated with it. These identifiers allow the downlink to be treated as if it is composed of multiple virtual downlinks. Virtual channels are used to differentiate data types, for example, real-time data from recorded data and science data from engineering data.

HISTORY OF CCSDS USE FOR FLIGHT MISSIONS AT GSFC

The original CCSDS telemetry Recommendations were defined in 1984, and the telecommand Recommendations were defined in 1987. The first mission to use both CCSDS telemetry and telecommand was SAMPEX, the first spacecraft from the Small Explorer Project. Other GSFC spacecraft that were developed in the 1980s (Hubble Space Telescope, Gamma Ray Observatory) used some of the CCSDS concepts but were designed prior to the completion of the CCSDS Recommendations. SAMPEX was built in-house by GSFC and was launched in July 1991. Four subsequent Small Explorer spacecraft were also built using these Recommendations. Another spacecraft built in-house at GSFC, the X-Ray Timing Explorer (XTE), was launched in 1995. This spacecraft uses the same telecommand Recommendations as the Small Explorers, and uses the AOS telemetry Recommendation instead of Packet Telemetry. This approach is being used by several other GSFC missions under development, including the Tropical Rainfall Measuring Mission, the first Earth Observing System (EOS) mission, and the Microwave Anisotropy Probe (MAP). This approach is expected to be used for all spacecraft developed by GSFC or developed elsewhere but managed by GSFC. Table 1 shows the usage of CCSDS telecommand and telemetry Recommendations by GSFC missions launched or to be launched from 1991 through 2000.

Table 1. CCSDS Usage by GSFC Missions

GSFC Mission	Spacecraft Builder	Launch Date	Telecommand	Telemetry
SAMPEX	GSFC	1991	Compliant	Packet Telemetry
FAST	GSFC	1995	Compliant	Packet Telemetry
SOHO	ESA	1995	No	AOS
XTE	GSFC	1995	Compliant	AOS
Wind/Polar	Lockheed-Martin	1995, 1996	No	No, time division multiplexed
ACE	APL	1997	Similar; modified error control, status reporting	Time division multiplexed within CCSDS frames
TRACE	GSFC	1997	Compliant	Packet Telemetry
TRMM	GSFC	1997	Compliant	AOS
EOS-AM	Lockheed-Martin	1998	Compliant	AOS
Landsat 7	Lockheed-Martin	1998	Similar, but not fully compliant	Time division multiplexed within CCSDS frames
WIRE	GSFC	1998	Compliant	Packet Telemetry
New Millennium E0-1	Litton	1999	Compliant	AOS
SWAS	GSFC	1999	Compliant	Packet Telemetry
IMAGE	Lockheed-Martin	2000	Compliant	AOS
MAP	GSFC	2000	Compliant	AOS

The XTE spacecraft implementation represents a good example of CCSDS use at GSFC. Each spacecraft subsystem is assigned a range of packet Application Process Identifiers (APIDs). This enables the APIDs to uniquely identify the source of the data. The data in the telemetry packets is collected by distributed data collection nodes in the subsystems. The telemetry packets are sent via a local area network to a central data collection subsystem, the Command and Data Handling subsystem (C&DH). The C&DH assembles the real-time telemetry data stream and records the telemetry data for later high-speed playback.

The XTE C&DH flight software multiplexes the telemetry packets into streams of VCDUs. Packets are selected, filtered, and organized into a number of virtual channels. The virtual channels are used to filter and/or route the data according to broad categories, such as real-time housekeeping, real-time science, playback housekeeping, and playback science.

The XTE C&DH also filters the data based on APID. The filter tables allow the C&DH to transmit and/or store every Nth packet received from the spacecraft subsystems. XTE filters packets for downlinking at frequencies between 1 and 1/256 of their on-board rates. Through the use of this filtering of packets, the housekeeping data collection rate on-board is 64 kilobits per second (kbps), the real-time housekeeping downlink rate is 16 kbps, and the housekeeping data storage rate is 9 kbps. This filtering scheme, enabled by the use of CCSDS Recommendations, allows the downlink data content to be adjusted by adjusting the filters, without modifying the on-board software.

The XTE C&DH also receives and distributes commands to each subsystem via the same network interface. Only one command virtual channel is used for XTE routine commanding. The C&DH processes each command and routes it to its destination based on the command APID. A second virtual channel is used for hardware discrete commands in order to allow a simple hardware decoder to be implemented on the uplink card. The virtual channel change allows the decoder circuitry to differentiate the special hardware commands from the normal commands based on the first 24 bits of the CCSDS command header.

BENEFITS OF CCSDS

Through the use of the CCSDS Recommendations, the mission implementation and operations have benefited by:

<u>Enabling reuse</u>
The system used for integration and test and for operations can be reused on other missions that use the same data system standards. This option provides the potential for large cost savings through the reuse of systems for missions that adhere to the same known and published standards. In addition, the operations risks are reduced because flight operations team members can re-apply the experience gained during operations on one mission to another mission that uses the same standards.

<u>Lowering the risk of transmitting command and receiving telemetry data</u>
By using a standard method for command and telemetry data rather than the ad-hoc methods previously developed for each mission, a project is assured that the protocols are mature and complete. Using the CCSDS Recommendations lowers the risk of the protocol’s being incomplete or having unintended consequences, because it has been evaluated in detail by experts from many space agencies and has been used by other spacecraft. The CCSDS telecommand Recommendation is a sophisticated protocol that offers better uplink utilization and more efficient recovery from communications errors than previous methods.

<u>Using the CCSDS path service for formatting telemetry data</u>
In previously used Time Division Multiplex (TDM) systems, the C&DH synchronously collected telemetry from different sources. The format of the data was a set of minor frames organized into a major frame. Telemetry points from the entire spacecraft were assigned specific positions within the major frame. Each mnemonic format and location was assigned globally by the data system engineer for TDM formatted telemetry. Modifications to the telemetry format were managed centrally and this was a very resource-intensive job, especially for projects in which subsystems and instruments were developed in geographically remote locations. In contrast, by using the CCSDS path service, each subsystem is

simply allocated a telemetry rate budget. The telemetry is multiplexed at the packet level and the details of the packet contents are left to the respective subsystem engineer. Only the total bandwidth is managed centrally, to ensure that the sum of the data generated by the subsystems does not exceed the downlink data rate.

Simplifying the monitoring and the managing of the bandwidth

With TDM, only a handful of telemetry modes were available for diagnostic use, such as memory dump mode, science mode, and engineering checkout mode. The diagnostic capability was severely limited in flexibility and had to be predefined at a detailed level. CCSDS formatted telemetry enables the mission to be much more flexible. For example, in the XTE implementation, on-board telemetry is communicated among subsystems with only a subset of the packets provided to the telemetry downlink. Subsystem telemetry is filtered for the telemetry downlink, with every Nth packet (different for each APID) routed to the transmitter. Each subsystem can manage its overall telemetry format and bandwidth simply by assigning appropriate filter factors to each of its different packets. XTE assigns different filter factors for its solid state recorder versus the real-time downlink.

The modification of a TDM format required replacing some data (often science data) with diagnostic data. Flight software or data commutation tables were rewritten. The operational flexibility of the CCSDS implementation was demonstrated when diagnosing the performance of XTE's star trackers. Star tracker packets are routed to the on-board attitude determination process at a frequency of 10 Hz. However, the packets are normally downlinked at a rate of only 1 Hz. When XTE attitude control system engineers detected anomalous behavior in the star tracker, the filter factor was updated to route the star tracker packets to the solid state recorder at the full rate of 10 Hz. The attitude control system engineers were able to receive the full data stream to diagnose the problem without affecting other subsystems and without changing the real-time bandwidth. The only modification to the telemetry format required was a single table element update and was accomplished within one day after management approval.

Using Commercial-Off-The-Shelf (COTS) hardware for telemetry decoding

The decoding of the data is performed in the operations control center for some missions. Use of the CCSDS Recommendation for coding has allowed these systems to use COTS decoders rather than more expensive and less proven custom decoders.

LESSONS LEARNED FROM THE USE OF CCSDS RECOMMENDATIONS

The CCSDS Recommendations are detailed, but they are vulnerable to individual interpretation. Two different organizations can take the same Recommendation and develop systems that will not interoperate completely. Implementers of systems based on CCSDS Recommendations should discuss their concepts with CCSDS experts to verify that they are interpreting the CCSDS documents correctly and to benefit from the lessons learned by other implementers. In addition, new CCSDS implementations need to carefully examine the influence that legacy elements may impose on the design and selection of CCSDS options.

End-to-End System Engineering

A significant lesson to be learned has to do with the process by which most missions went about designing the end-to-end, spacecraft-to-end-user data system. In some cases, the space segment of the data system was designed well ahead of the ground segment. The data system would be optimized for most effective utilization of on-board resources, but the impact to the ground segment was not considered until later. By the time these impacts were recognized, it was often too late to make adjustments on-board. This resulted in either costly additional software, additional operations workload, or both. The SOHO accommodation of the Michaelson Doppler Interferometer (MDI) instrument is a good example. The MDI instrument was based on a heritage design and its interfaces were used without modification. The MDI could not accept a spacecraft timing source to time stamp the packets that it generated. All of the other data sources on-board did provide a time stamp in the packets. This caused a problem for the ground processing of the data. Not only did MDI not provide a time stamp in the packet header (which is important to perform Level-0 processing), but it also differed from the rest of the spacecraft subsystems. This resulted in the development of a custom subsystem within the Level-0 processing software just to handle MDI data. This type of problem can be solved by effective systems engineering of the end-to-end data system. The mission must be designed end-to-end in order to make most effective use of CCSDS or any standard. Even more effective would be systems engineering of data systems across missions.

Selection of Class and Grade of Service

The CCSDS Recommendations are designed to encompass the requirements of a diverse set of users and organizations. The Recommendations include a variety of features and options to choose from. For example, the AOS Recommendation identifies six different services, each with up to three grades of service. The use of this Recommendation on GSFC missions has so far been limited to only one of the services (the path service) and one grade of service (grade 2: in-sequence and error free, but possibly incomplete). Users of CCSDS Recommendations need to select the subset of features and options that best meet their requirements. If interoperability with other organizations is required, the selected subset needs to include the features required to work with the other organization’s system.

Loss of Timing Relationships

The use of packets for the spacecraft status telemetry provides a flexible mechanism for reporting the configuration and state of the spacecraft. However, some of the timing relationships inherent in a time division multiplexed telemetry scheme could be lost in a packet telemetry implementation. Users need to think through their requirements for the timing of parameters and events and the relative timing between samples of a parameter when designing the packet telemetry implementation.

CCSDS Overhead

The overhead associated with CCSDS can be larger than that associated with TDM telemetry. The VCDU header and Reed-Solomon encoding symbols add approximately 16% overhead to the telemetry. Packet header overhead depends on the size of the data packets. For example, the average packet overhead for XTE engineering data is about 12% with a range from a low of 1.5% and to a high of 43% for the smallest packets.

Performance Requirements

The Submillimeter Wave Astronomy Satellite (SWAS) has a mode for initialization where the bandwidth is filled with very small status packets from the Attitude Control System. The data portion of these packets is smaller than the packet header and at high downlink rates result in nearly 15,000 packets per second. This exceeded the initial capabilities of the ground system. The more flexible data formatting capabilities enabled by the use of CCSDS require more analysis of the performance implications of the downlink design. In addition, this is an example of where early coordination among the spacecraft and ground system developers is needed to ensure compatibility.

Delegation of Packet Content Control

The use of packet telemetry allows the control of the contents of the packets to be delegated to the subsystem designers. This decentralization is enabled by the telemetry Recommendations, but is not part of the Recommendations themselves. If the control of the packet content is delegated, a bandwidth budget should be allocated along with it. Several GSFC missions had a significant oversubscription of the available bandwidth when all of the initial subsystem implementations were integrated, requiring a few iterations to make the data fit.

Data Bypass

A goal of the CCSDS telemetry Recommendation is to allow the operations center to receive only the subset of the data that it required to monitor the space components. All of the voluminous science data would not have to go to the operations center, as it did in TDM telemetry implementations. This significantly reduces the volume of data that the operations center handles. This goal has been elusive, however. Several missions have found late in their development that certain parameters in the science data stream were required in the operations center in order to perform data accounting or instrument performance evaluation. Future missions that wish to accomplish this goal will have to exercise more foresight in identifying the subset of data required in the operations center early in the design phase.

FUTURE NEEDS FOR CCSDS RECOMMENDATIONS

File Transfer Protocol

CCSDS has provided a set of Recommendations for the space/ground communications link. Further, the CCSDS is considering an extension of their Recommendations to support file transfer between ground and space. This protocol would be used to move data from on-board solid state recorders to the ground, to uplink software and tables, and to downlink memory dumps. This Recommendation will benefit flight operations, since these functions are all implemented in different ways by different spacecraft builders. The benefits of this Recommendation are similar to those of the existing Recommendations–a robust and proven protocol, reuse of flight operations software, and reuse of flight operations team experience from mission to mission.

Past experience and emerging future requirements suggest that a file transfer protocol must:

a. accommodate data rates up to 100s of million bits per second (for missions such as EOS);
b. accommodate moderate communications latencies of 5 seconds or less;
c. provide bi-directional file transfers both from the ground to the spacecraft and from the spacecraft to the ground;
d. be consistent with the existing CCSDS Recommendations;
e. span space/ground contacts;
f. internetwork with standard ground file transfer protocols.

Supercommutation

In the XTE C&DH implementation, each telemetry packet contains a single sample of each telemetry data point. The set of samples is collected, time tagged, and included into a single telemetry packet. For small sets of data collected frequently, the bandwidth associated with the header and time tag could be substantially larger than the data bandwidth. A convention has been established for future missions to collect multiple sets of the telemetry data sets and to concatenate them together into a single packet, thereby reducing the relative overhead of the header and time tag to arbitrarily low levels. A CCSDS Recommendation for this process, called supercommutation, would be beneficial.

Application Layer Standards

Spacecraft development and flight operations will benefit from applications layer standards that would standardize functions common to most spacecraft. Some examples are stored command formatting, on-board processor logs, flight software table formats and loading and dumping mechanisms, and on-board data management. These functions are implemented in similar fashion from spacecraft to spacecraft. Standards in these areas will allow even greater autonomy in the flight and ground data systems development and in operations. However, as application layer functions, they must be integrated with the more mission-unique spacecraft functions. It may be difficult to define a flexible and efficient interface between standard applications functions that would be widely adopted. The challenge with application layer standards is that standardization tends to constrain future innovation. CCSDS should explore the feasibility of application layer standards, but should not commit to them unless there is a consensus for the need for these standards among the member organizations of CCSDS.

CONCLUSION

The use of CCSDS Recommendations has provided GSFC flight missions with robust and capable protocols for command and telemetry data. It has reduced costs by increasing the reuse of existing solutions and has lowered risk by allowing spacecraft testing and flight operations teams to reuse their experience from one mission to the next. CCSDS use for telemetry enables improvements in the efficiency of the process of formatting the telemetry for a mission. However, the CCSDS Recommendations should be implemented in consultation with CCSDS experts, since they can be improperly applied in ways that were not intended by the Recommendations, and in ways that will not interoperate with other CCSDS implementations. CCSDS Recommendations should be extended to include file transfer protocols to provide a standard mechanism for moving large amounts of data between space and ground. In addition, CCSDS should investigate the feasibility of establishing applications layer standards between the spacecraft and flight operations function.

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These documents are available at “http://www.ccsds.org/ccsds/”.